XII. QUE 94201

Basalt, 12 grams

Weathering Be

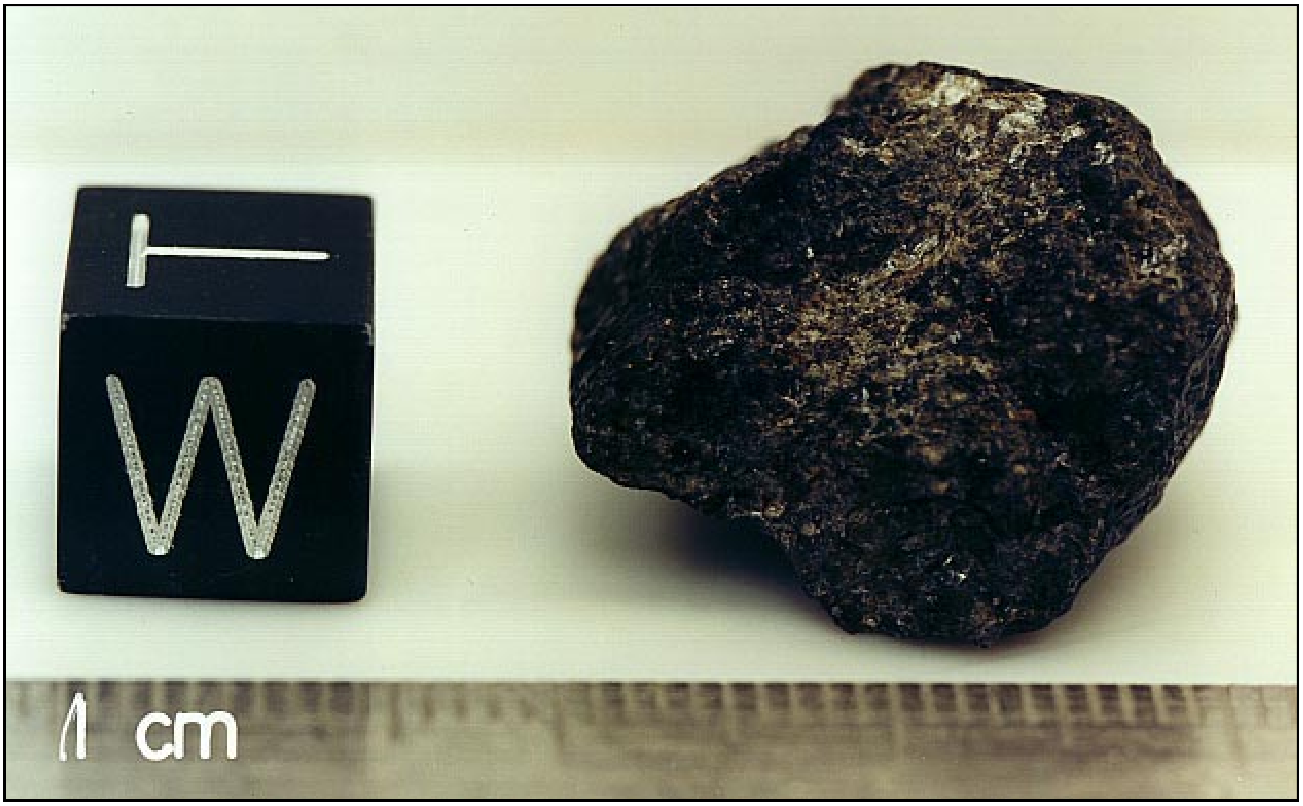

Figure XII-1. *Photograph illustrating broken interior surface of Martian meteorite QUE94201. (NASA # S96-00376)*

Introduction

Five sides of QUE94201 are rounded and polished with remnant fusion crust, while one side appears freshly broken (figure XII-1). The interior is coarse-grained, crystalline and glassy (Score and Mason, 1995). "Mafic-rich areas" (probably shock-melted glass), as large as 5 x 4 mm, were noted during preliminary examination. In thin section, the sample is made up of subequal amounts of homogeneous maskelynite laths and variable interstitial pyroxene. Maskelynite laths are up to 3.6 mm long.

QUE94201 is a basalt apparently similar to the dark, mottled lithology (DML) of Zagami (McSween *et al.*, 1996) as well as "lithology B" of EETA 79001 (Mikouchi *et al.*, 1998). However, the phosphorous content of QUE94201 is high and the REE pattern is strongly depleted in light rare earth elements. The extreme zoning in pyroxene in QUE94201 indicates that it cooled quickly from magmatic temperatures. The Fe-Ti oxide compositions indicate that this basalt formed under more reducing conditions than the other shergottites (McSween *et al.*, 1996).

Petrography

Harvey *et al*. (1996) describe QUE94201 as a *"coarse-grained basalt, consisting of subhedral Fe-rich pigeonite and maskelynite"*. Most of the pyroxene and maskelynite grains exceed 1 mm in length (up to 3 mm) and are somewhat elongated (figure XII-2). The mineral mode is approximately 44% clinopyroxene (pigeonite to augite 77:23), 46% maskelynite, 2% opaques, 4% whitlockite, 4% mesostasis.. QUE94201 contains relatively high proportions of maskelynite and whitlockite when compared with the other shergottites. No melt

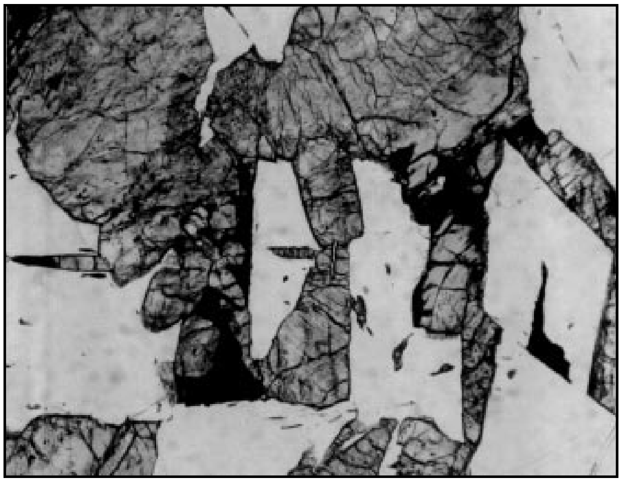

Figure XII-2. Photomicrograph of thin section of QUE94201,4 illustrating basaltic texture. Field of view is 2.2 mm.

inclusions were noted in the pyroxene.

The pyroxenes in QUE94201 are complexly zoned (McKay *et al.,* 1996; Mikouchi *et al.,* 1996; 1998 and McSween and Eisenhour, 1996). The Mg-rich pigeonite cores are mantled by Mg-rich augite, which is, in turn, rimmed by Fe-rich pigeonite and strongly zoned to pyroxferroite. None of the cores appear to be cumulate phases, as was the case for Shergotty, Zagami and EETA79001B. Some of the pyroxenes in QUE94201 are sector zoned.

Interstitial to the pyroxene and shocked plagioclase, are a number of late-stage phases including large Fe-Ti oxides (ulvöspinel, rutile, ilmenite), whitlockite and large "pockets" of mesostasis similar to the "DN pockets" of Zagami (McCoy *et al.,* 1995). These "pockets" contain an intergrowth of silica and fayalite, as well as, maskelynite, whitlockite, Fe-Ti oxides, sufides, minor augite, chlorapatite and a Zr-rich phase, probably baddelyite. Fayalite-silica intergrowths are also found in the cores of large skeletal phosphate grains adjacent to these pockets (Harvey *et al.,* 1996).

Shock features include maskelynite, mosaicism in pyroxene and large pockets of glass formed *in-situ*. The shock-melted glass is rich in phosphorous (Mikouchi *et al.,* 1998).

Mineral Chemistry

***Pyroxene*:** Pyroxene zoning is extreme (figure XII-3), including sector zoning in the cores (Kring *et al.,* 1996; Mikouchi *et al*., 1996, 1998; McKay *et al*., 1996;

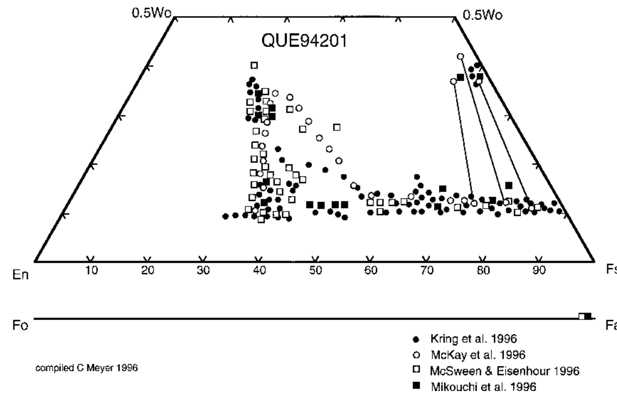

Figure XII-3. *Composition diagram for pyroxene and olivine in QUE94201. Data are from Kring et al. (1996), McKay et al. (1996), McSween and Eisenhower (1996) and Mikouchi et al. (1996). Olivine is pure fayalite.*

McSween and Eisenhour, 1996). Harvey *et al.* (1996) report pigeonite zoning to Fs_{85}. Wadhwa and Crozaz (1996), McSween *et al.* (1996) and Wadhwa et al. (1998) have determined the REE patterns of the pyroxenes.

***Plagioclase*:** Plagioclase (An_{66-52}) crystallized late in the crystallization sequence (McSween and Eisenhour, 1996). It has been shocked to maskelynite.

***Phosphates*:** QUE94201 contains more whitlockite than other SNC meteorites. The whitlockite has been studied by Wadhwa and Crozaz (1996) and is found to have a more extreme depletion of LREE than for any other shergottite. Mikouchi *et al.* (1998) analyzed "merrillite" up to 3 mm long.

***Apatite*:** Mikouchi *et al.* (1996), McSween *et al.* (1996) and Leshin *et al.* (1996) also report minor chlorapatite.

***Silica*:** Silica occurs as distinctive intergrowth with fayalite in "patches" up to 1 mm in-between pyroxene and plagioclase grains (Harvey *et al*., 1996). Silica was also reported as an alteration product by Wentworth and Gooding (1991).

***Olivine*:** Fayalite (Fa_{96-99}) occurs as a fine dendritic intergrowth with silica (Harvey *et al*., 1996).

Pyroxferroite: An analysis of pyroxferroite is given in Mikouchi *et al.* (1998).

***Opaques*:** Analyses for ilmenite and ulvöspinel are reported in Kring *et al.* (1996) and McSween *et al.* (1996).

***Sulfide*:** The sulfide phase is pyrrhotite (McKay *et al.*, 1996; McSween and Eisenhour, 1996).

Glass: QUE94201 contains abundant pockets of shock-melted glass. This melt contains up to 7 % P, probably due to preferential melting of the abundant phosphates (Mikouchi *et al*., 1996, 1998).

***Salts*:** Fe-K-sulfates are sometimes observed rimming Fe-sulfides (Harvey *et al.*, 1996). The salts have been studied in detail by Wentworth and Gooding (1996). They found that "*carbonates are conspicuously absent.*"

Whole-rock Composition

The chemical composition of QUE94201 has been determined and reported by Dreibus *et al.* (1996), Warren and Kallemeyn (1996, 1997) and Mittlefehldt and Lindstrom (1996). The sample has very high phosphorous content (table XII-1). This is also reflected in the analysis of the fusion crust and modal mineralogy of the thin sections (Kring *et al.*, 1996; Mikouchi *et al.*, 1996).

QUE94201 is a basalt that is greatly depleted in LREE (figure XII-4).

Radiogenic Isotopes

Borg *et al.* (1996, 1997) reported a Rb-Sr age (λ_{Rb} = 1.402 x 10^{-11} $year^{-1}$) of 327 ± 12 Ma with initial $^{87}Sr/^{86}Sr$ ratio of 0.701298 ± 14 (figure XII-5). This low I_{Sr} ratio indicates that the source region (Martian mantle) was depleted in Rb. The Sm-Nd age of 327 ± 19 with ε_{Nd} = 47.6 ± 1.7 is conordant with the Rb-Sr age (figure XII-6). Dreibus *et al.* (1996b) reported a K/Ar age of 1.33 Ga.

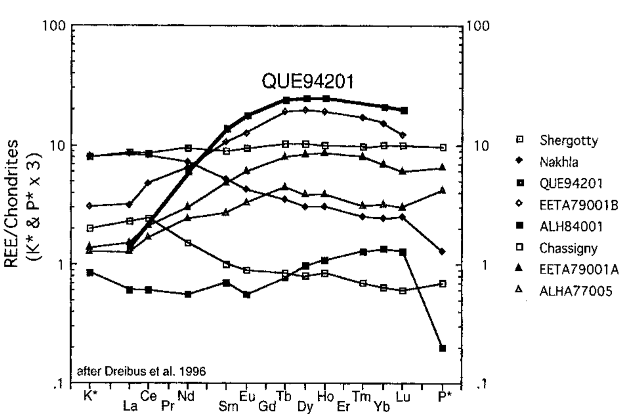

Figure XII-4. *Normalized rare earth element diagram for QUE94201 compared with data for other Martian meteorites.*

Cosmogenic Isotopes and Exposure Ages

From cosmic-ray produced ^{3}He, ^{21}Ne and ^{38}Ar, Eugster *et al.* (1996) computed an exposure age for QUE94201 of 2.4 ± 0.6 Ma and concluded that QUE94201 was "*ejected from Mars simultaneously with the other basaltic shergottites - Shergotty and Zagami*". Nishiizumi and Caffee (1996) found the ^{10}Be concentrations gave a cosmic-ray exposure age of 2.6 ± 0.5 Ma for an assumed 4π irradiation geometry. Garrison and Bogard (1998) determined a cosmic ray exposure age of 2.7 ± 0.6 Ma. Dreibus *et al.* (1996b) also reported exposure ages.

Nishiizumi and Caffee (1996) found that the terrestrial age (0.29 ± 0.05 Ma obtained from ^{36}Cl) of QUE94201 is longer than for other Antarctic shergottites. Jull *et al.* (1997) found that ^{14}C activity was nil, consistent with an old terrestrial age

Other Isotopes

Oxygen isotopes were reported by Clayton and Mayeda (1996) (figure I-2). Leshin *et al.* (1996) have determined that the hydrogen in six "*apatite*" grains in QUE94201 has a high D/H ratio, probably from the Martian hydrosphere.

Grady *et al.* (1996) reported that the carbon released from 450 to 600°C was isotopically light ($\delta^{13}C$ ~ -24.2 ‰).

Eugster *et al*. (1996), Swindle *et al*. (1996) and Garrison and Bogard (1998) determined the contents and isotopic ratios of rare gases (Ne, Ar, Kr, Xe) in QUE94201 and found them typical of other shergottites. Small amounts of ^{21}Ne produced by energetic solar protons may be present in QUE94201 (Garrison and Bogard, 1998). Garrison and Bogard's (1998) study was for unmelted mineral phases.

Blichert-Toft *et al.* (1998) found a very large Hf isotopic anomaly - to match the large ^{142}Nd isotopic anomaly as determined by Borg *et al.* (1997). *These isotopic anomalies have been preserved in the source region of Martian basalts, since the initial early formation of the crust of Mars!*

Weathering

Wentworth and Gooding (1996) have studied the weathering products in QUE94201. They report an abundance of Fe-sulfate, but since this is also observed in cavities in the fusion crust, this is almost certainly a

Table XII-1. Chemical composition of QUE94201.

	Warren96		Dreibus96		Kring 96		Kring 96		Mikouchi96		Mittlefehldt 96		Warren 97	
weight	*305 mg*		*179.8 mg*		*250mg*		*fusion crust*		*fusion crust*		*52.74 mg*		*305 mg*	
SiO2 %	47.06	(a)					43.5	(d)	44.3	(d)			48.00	(d)
TiO2	1.95	(a)	1.8	(b)	1.7	(b)	1.81	(d)	2	(d)			1.98	(b)
Al2O3	9.64	(a)	12	(b)	11.1	(b)	7.46	(d)	7	(d)			9.82	(b)
FeO	18.65	(a)	18.3	(b)	18.3	(b)	24.2	(d)	21	(d)	20.0	(b)	19.16	
MnO	0.48	(a)	0.436	(b)	0.44	(b)	0.63	(d)	0.6	(d)			0.47	(b)
CaO	11.3	(a)	11.3	(b)			10.9	(d)	11.2	(d)	10.7	(b)	11.48	
MgO	6.3	(a)	6.2	(b)			6.04	(d)	6.4	(d)			6.3	(d)
Na2O	1.39	(a)	1.75	(b)			1.16	(d)	1.1	(d)	1.53	(b)	1.39	
K2O	0.038	(a)	0.052	(b)			0.04	(d)					0.04	
P2O3							2.77	(d)	3.4	(d)				
sum	**96.81**						**98.51**		**97**				**98.64**	
Li ppm														
C														
F			40	(b)										
S														
Cl			91	(b)										
Sc	49	(b)	46.6	(b)							51.5	(b)	49.0	(b)
V	124	(b)	103	(b)									124	
Cr	1030	(b)	890	(b)									1010	
Co	24.4	(b)	22.8	(b)							25.9	(b)	24.4	
Ni	<40	(c)	<20	(b)									<40	
Cu														
Zn	108	(c)									130		108	
Ga	26	(b)	27.1	(b)									25.9	
Ge														
As			0.77	(b)										
Se														
Br			0.35	(b)			**Borg 97**		**Borg 97**		0.38			
Rb				(b)			0.518	(f)	0.691	(f)			<6	
Sr	59	(b)	80	(b)			41.3	(f)	49.8	(f)	70		59	
Y			31.2	(e)										
Zr	94	(b)	97.1	(e)							80		94	
Nb			0.68	(e)										
Mo														
Pd ppb														
Ag ppb														
Cd ppb														
In ppb														
Sb ppb														
Te ppb														
I ppm			4.6	(b)										
Cs ppm													<0.12	
Ba	<41	(b)	<15	(b)									<41	
La	0.44	(b)	0.35	(b)							0.31		0.44	
Ce	1.63	(b)	1.3	(b)							1.0		1.63	
Pr							**Borg 97**							
Nd	2.4	(b)	1.9	(b)			1.482	(f)					2.36	
Sm	2.55	(b)	2.02	(b)			1.233	(f)			1.92		2.55	
Eu	1.09	(b)	0.99	(b)							0.9		1.09	
Gd			4.3	(b)										
Tb	0.93	(b)	0.802	(b)							0.78		0.93	
Dy	6.1	(b)	5.53	(b)										
Ho			1.19	(b)										
Er														
Tm														
Yb	3.5	(b)	3.09	(b)							3.02			
Lu	0.54	(b)	0.455	(b)							0.42		0.54	
Hf	3.4	(b)	3.42	(b)							4.2		3.4	
Ta	<0.08	(b)	0.023	(b)							0.03		<0.08	
W ppb														
Re ppb														
Os ppb														
Ir ppb	<2.4	(b)	<3	(b)									<2.4	
Au ppb			<1.5	(b)									<0.5	
Tl ppb														
Bi ppb														
Th ppm	<0.09	(b)	0.05	(e)									<0.09	
U ppm			0.0125	(e)									<0.2	

technique: (a) emp fused bead, (b) INAA, (c) RNAA, (d) emp, (e) spark sourrce mass spec., (f) isotope dilution mass spec.

weathering product of Antarctic origin (Harvey *et al.*, 1996).

Processing

This small sample (12.0 g) has some remnant fusion crust which is difficult to distinguish from interior glass. The sample was initially thought to be a terrestrial rock, but the presence of maskelynite in thin section revealed its Martian origin. Allocations were made from small interior and exterior chips. Two potted butts were used to produce 12 thin sections (table XII-2).

QUE 94201 is listed as a “restricted” sample by the MWG (Score and Lindstrom, 1993, page 5) because of its small size.

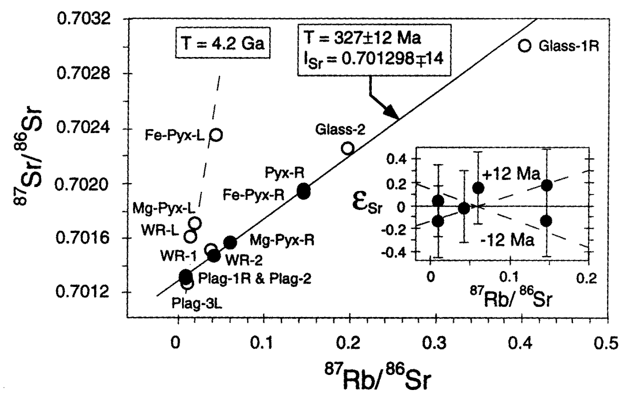

Figure XII-5. *Rb-Sr mineral isochron for QUE94201 as reported by Borg et al. (1997, GCA **61**, 4920).*

Table XII-2. Thin sections of QUE94201.

butt	section	1998	previous parent	figure in
,2				,0
	,3	Mason		
	,4	MCC		
	,5	McSween		
	,6	Papike	Harvey	
	,7	Kring		
	,8	Delaney	Gooding, Yanai	
	,9	McKay, D	Mittlefehldt	
,20				,0
	,34	Mikouchi		
	,35	Dreibus		
	,36	Warren		
	,37	Mittlefehldt		
	,38	Harvey		

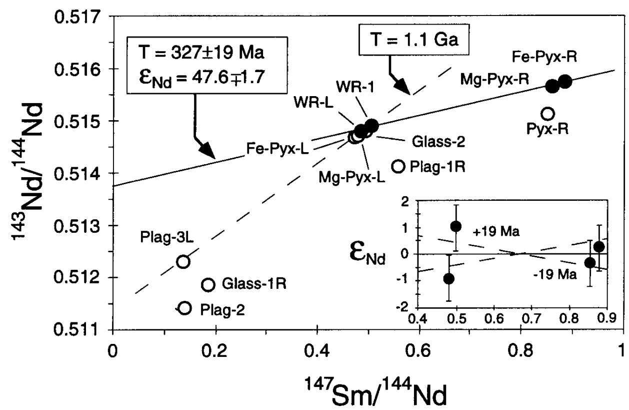

Figure XII-6. *Sm-Nd isochron plot for pyroxene and ‘whole rock’ separates from QUE94201 determined by Borg et al. (1997, GCA **61**, 4921).*